#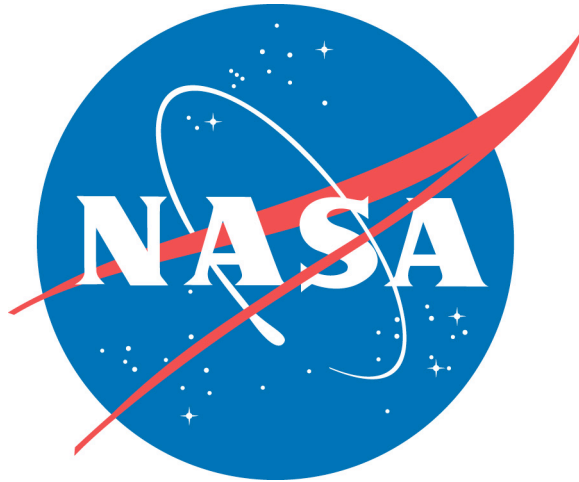 Verification & Validation Report for "Integrated forecasting system for mitigating adverse space weather effects on the Northern American high-voltage power transmission system"

NASA Goddard Space Flight Center in partnership with the Electric Power Research Institute

Acknowledgments

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Executive Summary

The Solar Shield[1] project responds to the NASA Strategic Goal 3, Sub-goal 3A: "Study Earth from space to advance scientific understanding and meet societal needs" as described in the 2006 NASA Strategic Plan. The project is funded by the NASA Applied Sciences Program, which has the objective to expand and accelerate the economic and societal benefits from Earth science, information, and technology. The project is managed within the NASA Applied Sciences Program's "Weather" program element.

In this project, an enhancement to the Electrical Power Research Institute's (EPRI) SUNBURST decision support tool used by the U.S. electric power industry is developed by prototyping a Geomagnetically Induced Current (GIC) forecasting system for the effects of solar activity on the North American power grid. The forecasting system will consist of a chain of state-of-the-art space physics models describing the coupled Sun-Earth system. Predictions of GIC flowing in the power transmission system are derived from the model chain output and are used to create products for the end-user making decisions about possible GIC mitigation actions.

Models employed by the forecasting system are resident at the Community Coordinated Modeling Center (CCMC) located at the NASA Goddard Space Flight Center in Greenbelt, Maryland. These models, which have been developed using NASA resources by the space research community, have been provided to the CCMC for research simulation and evaluation of space weather applications, such as the one discussed in this document.

The model chain will be driven by solar data from NASA missions such as SOHO, or from ground-based observatories. Additionally, NASA's ACE spacecraft, which is located upstream from the Earth, will provide a second source of driver data for the magnetosphere/ionosphere component of the model chain.

In this document a) the design and the real-time implementation of the GIC forecasting system is described in detail and b) system verification and validation activities associated with Solar Shield are described. The established GIC forecasting system is composed of two partially separate components providing long lead-time Level 1 and short lead-time Level 2 estimates. Two different approaches for verifying and validating the two levels of the system are devised and executed. The analyses, to be updated periodically as the system is run, indicate that despite the difficulties associated with analyzing rare extreme events, both Level 1 and Level 2 forecast accuracies are good enough to have potential for generating monetary benefit for the user of the system.

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[1] Throughout the text we will, for brevity, refer to the activity as "Solar Shield"

1.0   Introduction

The activity discussed in this document seeks to enhance the capabilities of the Electrical Power Research Institute's (EPRI) SUNBURST decision support tool used by the U.S. electric power industry by prototyping a Geomagnetically Induced Current (GIC) forecasting system for the effects of solar activity on the North American power grid. The forecasting system consists of a chain of models, which transmit plasma and magnetic fields and their dynamics from the solar surface and heliosphere, to the magnetosphere of the Earth, and then into the Earth's ionosphere. GIC flowing in the power transmission system and the geoelectric field driving GIC will be derived from these ionospheric currents. By using real-time space-based observations (carried out by NASA) of near-space conditions and the developed model chain, GIC forecasts can be derived to individual sites of the North American power transmission system. These forecasts, together with other real-time information available via SUNBURST network can then be used by operators of the transmission system to mitigate the potentially harmful effects of solar activity on the North American grid.

In this report the current implementation of the experimental forecasting system is described in detail. The coupling of the system to the SUNBURST decision support tool used by the electric power transmission industry is also explained. The established forecasting system is composed of two partially separate components providing long lead-time Level 1 and short lead-time Level 2 estimates. Consequently, two different approaches for verifying and validating (V&V) the system are used. The core part of the report describes the methods and the results of the chosen V&V approach.

2.0   Design and implementation of the forecasting system

The identified two-level system requirements (see *Evaluation Report,* 2008) led to the development of two partly separate forecast products: a) Level 2 product based on in situ Lagrange 1 (L1) point solar wind observations and magnetospheric magnetohydrodynamic (MHD) simulations and b) Level 1 product based on remote solar observations and heliospheric MHD simulations. The major differences between the products are that they are driven with different input observational data and whereas Level 2 GIC forecasts are fully deterministic, Level 1 forecasts are partly probabilistic. The two products are described in detail below. Tables 1 and 2 summarize the NASA data and models used in the forecasting system. The two-level system has been running in real-time since February 2008.

Table 1. NASA data products used to drive the GIC forecasting system.

Satellite	Sensors	System Operator	Product	Use in the forecasting system
ACE	MAG, SWEPAM	NASA	Plasma and magnetic field observations at L1.	To drive magnetospheric MHD models used for Level 2 GIC forecasts.
SOHO	MDI, LASCO	NASA/ESA	Solar magnetograms, CME observations.	To drive heliospheric MHD models used for Level 1 GIC forecasts.

Table 2. NASA models used in the GIC forecasting system.

Model	Input	Product	Use in the forecasting system
WSA, potential/empirical model of the inner heliosphere.	Solar magnetograms.	Plasma parameters and the magnetic field in the inner heliosphere.	Input to heliospheric MHD model used for Level 1 GIC forecasts.
ENLIL, MHD model of the heliosphere.	Plasma parameters and the magnetic field in the inner heliosphere.	Plasma parameters and the magnetic field in the heliosphere.	Input to magnetospheric MHD models used for Level 1 GIC forecasts.
BATSRUS, MHD model of the magnetosphere-ionosphere system.	Plasma parameters and the magnetic field in the vicinity of the solar wind-magnetosphere boundary.	Plasma parameters and the magnetic field in the magnetosphere. Electrodynamic parameters in the ionosphere.	Input to the geomagnetic induction and GIC computations at high latitudes. Used for both Level 1 and Level 2 GIC forecasts.
OpenGGCM, MHD model of the magnetosphere-ionosphere system.	Plasma parameters and the magnetic field in the vicinity of the solar wind-magnetosphere boundary.	Plasma parameters and the magnetic field in the magnetosphere. Electrodynamic parameters in the ionosphere.	Input to the geomagnetic induction and GIC computations at high latitudes. Used for both Level 1 and Level 2 GIC forecasts.
CRCM, kinetic model of the inner magnetosphere.	Plasma parameters and the electric field at the outer boundary of the inner magnetosphere. Magnetic field in the inner magnetosphere.	Plasma conditions in the inner magnetosphere. Electrodynamic parameters in the ionosphere.	Input to the geomagnetic induction and GIC computations at low latitudes. Used for both Level 1 and Level 2 GIC forecasts.
Geomagnetic induction model by A. Pulkkinen.	Ionospheric electric current distribution.	Geoelectric field and GIC at given locations.	Provides the final computational output of the forecasting system.

Level 2 Forecasts

Level 2 GIC forecasts are driven by in situ solar wind observations carried out at the Lagrange 1 point about 1.5 million kilometers upstream of the Earth (Fig. 1). In an ideal case, depending on the structure and the speed of the solar wind, Level 2 forecasts can give 30-60 minute lead-time for the end-user to react. It is noted that although this is relatively short lead-time, there are some procedures the operator of the transmission system can follow to mitigate the impacts of GIC in less than 60 minutes.

The Lagrange 1 solar wind observations carried out by MAG magnetometer (*Smith et al.*, 1998) and Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) (*McComas et al.*, 1998) instruments onboard NASA's Advanced Composition Explorer (ACE) are used to drive a global magnetospheric MHD model in real-time. Shortly, MHD describes magnetospheric plasma as a single electrically conducting fluid experiencing not only "regular" forces acting on fluid but also electromagnetic forces. Although this is only approximate description of complex space plasma, MHD successfully reproduces many of the central dynamical features of the magnetosphere.

An important feature of modern magnetospheric MHD models is that they are coupled to ionospheric electrostatic modules. The ionospheric module provides quasi-static description of the spatiotemporal behavior of the ionospheric currents responsible for high-latitude GIC. The connection between the ionospheric MHD output and GIC is established in Solar Shield in two steps (for details see, *Pulkkinen et al.*, 2007a). First, ionospheric currents generated by MHD are used in geomagnetic induction module that will provide the geoelectric field on the surface of the Earth. The geoelectric field is then used to compute GIC at desired location of the individual power transmission system. It should be noted that the two steps are strongly dependent on the local ground conductivity structure and on the electrical and the topological properties, or shortly the system parameters, of the transmission system of interest. Optimal ground conductivity and the system parameters are determined from the geomagnetic field and GIC observations by applying the methods developed by *Pulkkinen et al.* (2007b).
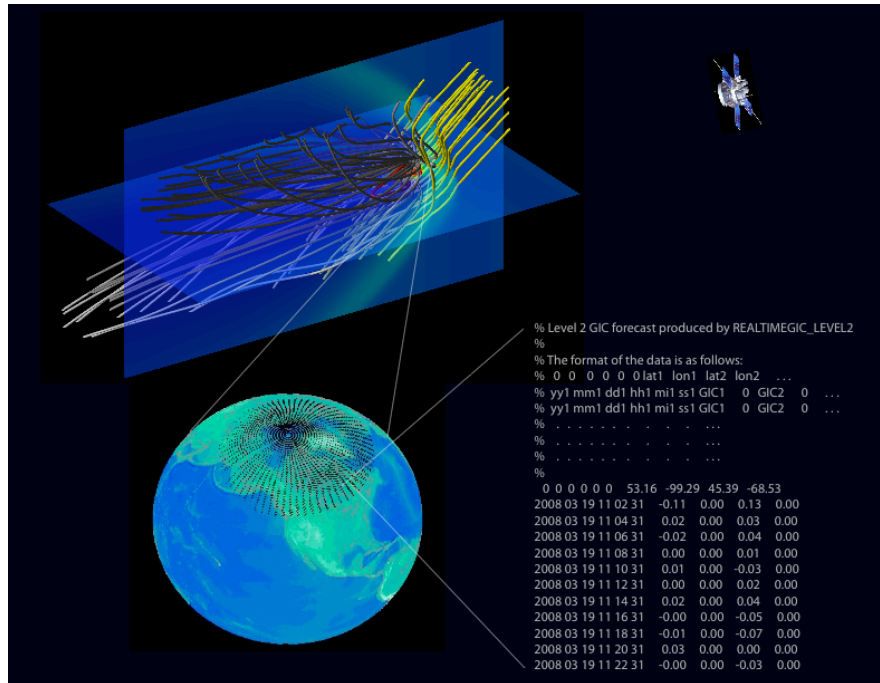
Fig. 1. The process used to generate Level 2 GIC forecasts. Lagrange 1 point solar wind observations carried out by ACE are used to a drive global magnetospheric MHD model. The ionospheric current output of the MHD model is used to compute GIC at individual power transmission system nodes. The final output of the system is given as a text file, which is provided to EPRI for integration into the SUNBURST decision support tool. The MHD, ionospheric current and GIC data shown in the figure are from an actual model run.

The current implementation of Level 2 forecasts uses real-time Block-Adaptive-Tree-SolarWind-Roe-Upwind-Scheme (BATS-R-US) MHD model (*Powell et al.*, 1999) runs carried out at CCMC. The forecasts generated for individual power transmission system nodes are stored into a text file (see Fig. 1), which is then downloaded for the usage in EPRI's SUNBURST decision support tool to be discussed below. In the current setting of the forecasting system Level 2 forecasts are updated every ten minutes.

Level 1 Forecasts

Although also Level 2 products play an important role in the forecasting system, Level 1 GIC forecasts are, due to the longer lead-time associated with the product, generally of more importance to the end-user. In principle, one could try to implement Level 1 forecast utilizing all the available information about solar and heliospheric conditions, such as location and structure of high-speed streams originating from solar coronal holes. However, the economic analysis carried by EPRI emphasizes the large potential cost associated with extreme GIC events. Thus, the current implementation of the system focuses in forecasting only disturbances associated with coronal mass ejections (CMEs), which are to our present understanding the solar events driving the

most severe space weather conditions. Depending on the speed of the approaching CME, Level 1 forecasts can give 1-2 day lead-time for the end-user to react.
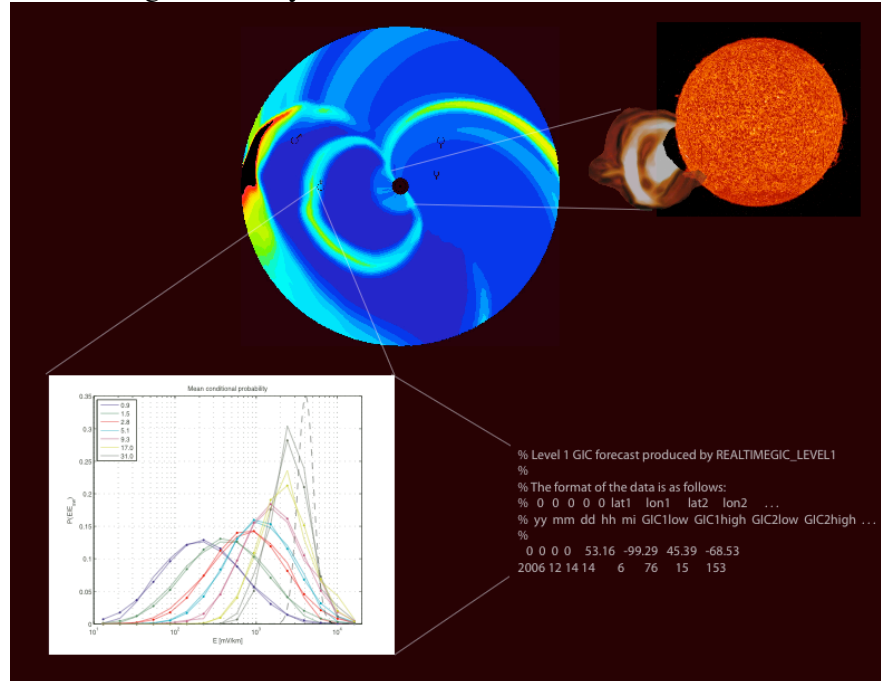

Fig. 2. The process used to generate Level 1 GIC forecasts. Solar observations (LASCO instrument onboard the SOHO spacecraft) of CMEs are used to initiate a transient disturbance at the inner boundary of a heliospheric MHD model that propagates the CME to the Earth. The modeled MHD parameters at the Earth are used in a statistical model coupling solar wind bulk properties to GIC at individual power transmission system nodes. The final output of the system is given as a text file, which is provided to EPRI for integration into the SUNBURST decision support tool. The CME, heliospheric MHD and GIC shown in the figure are real LASCO, ENLIL heliospheric MHD model (ecliptic view) and Level 1 forecast data. Note, however, that the image of the Sun is not produced by LASCO but by Extreme ultraviolet Imaging Telescope (EIT) instrument also onboard SOHO.

The following process is used to generate Level 1 forecasts (Fig. 2). First, solar observations of CMEs carried out by Large Angle and Spectrometric Coronagraph Experiment (LASCO) instrument (*Brueckner et al.*, 1995) onboard NASA/ESA Solar and Heliospheric Observatory (SOHO) located at the Lagrange 1 point are used to set the parameters of the so-called cone model (*Xie et al.*, 2004). The cone model parameters that approximate CME as a plasma cone are then used to introduce an over-pressured plasma transient at the inner boundary of the ENLIL heliospheric MHD model by *Odstrcil and Pizzo* (1999). ENLIL (named after an ancient god of wind) is used to propagate the observed solar disturbance through ambient solar wind, which in turn is modeled by using synoptic solar magnetograms (*Odstrcil et al.*, 2005), to the Earth and the modeled MHD parameters are used to generate an estimate for expected GIC levels. As current heliospheric MHD models are unable to reproduce the fine structure of the turbulent solar wind, probabilistic coupling between the bulk properties of the solar wind and GIC at individual stations is used generate the final Level 1 GIC forecast. The coupling is established by methods developed by *Pulkkinen et al.* (2008) and by using the

local ground conductivities and system parameters derived by the methods developed by *Pulkkinen et al.* (2007b). The Level 1 forecast approach is described in detail in *Pulkkinen et al.* (2009). It should be noted that, in principle, heliospheric MHD model output could be used as an input to a magnetospheric MHD model that would then provide fully first-principles-based estimates for GIC. However, it remains unclear if "smooth" heliospheric MHD output can generate large enough fluctuations in magnetospheric MHD required for large GIC. The matter is being studied at CCMC.

The current implementation of Level 1 forecasts uses ENLIL heliospheric MHD model runs that are carried out at CCMC. The up-to-date ambient solar wind is determined by means of Wang-Sheeley-Arge model (e.g., *Arge et al.*, 2004) and Mount Wilson Observatory synoptic solar magnetograms (*Howard*, 1976). The generated Level 1 GIC forecasts for different stations are stored into a text file (see Fig. 2), which is then downloaded for the usage in EPRI's SUNBURST decision support tool. Level 1 forecast is updated every time a new Earth-directed CME has been observed by SOHO/LASCO.

Coupling of the Forecasting System to the SUNBURST Decision Support Tool

The raw Level 1 and 2 GIC forecast products are useless from the end-user viewpoint unless they are "packaged" in a form that the user can efficiently utilize. The packaging is made in Solar Shield by coupling forecasts to EPRI's SUNBURST Decision Support Tool (DST). As an aftermath of the March 1989 space weather superstorm EPRI launched so-called SUNBURST project, whose primary purpose is to monitor GIC levels in members' power transmission systems (*Lesher et al.*, 1994). Consequently, current SUNBURST DST provides nowcasting of elevated GIC levels and is used by subscribing electric power companies to provide an indication of when and where a potentially damaging GIC event has occurred.
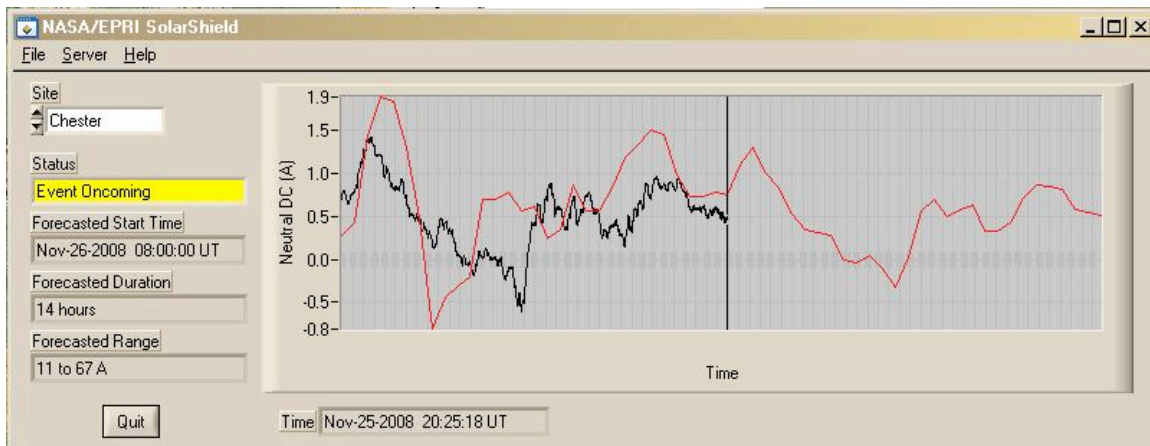
Fig. 3. Draft "control room" extension of the SUNBURST DST that uses information from both Level 1 and Level 2 GIC forecasts. Left-hand side of the display provides information about Level 1 forecast and the right-hand side shows both the observed GIC and Level 2 forecast.

Solar Shield seeks to enhance the SUNBURST DST by providing, in addition to existing nowcasting, novel GIC forecasting capability. This will for the first time enable EPRI's member power utilities to take preventative action under certain circumstances. The integration of the power system node-specific Level 1 and Level 2 forecasts generated at CCMC to SUNBURST DST hosted by EPRI is established via forecast files shown in Figs. 1 and 2. The forecast data will be inserted into the extension of the SUNBURST DST shown in Fig. 3. The information depicted on the enhanced DST can be considered as the ultimate end product of the GIC forecasting system. The decisions made based on the information provided by the enhanced DST link solar-terrestrial phenomena from the surface of the Sun to the surface of the Earth and to individual households that use the electric power provided by the transmission system affected by GIC.

In the current implementation of the system, EPRI downloads the forecast files associated with Level 1 and Level 2 forecasts from ftp server located at CCMC. The forecast files are then processed and the information is displayed in the control room extension of the SUNBURST DST shown in Fig. 3. The newly developed extended DST is being tested by EPRI. The forecast information will be made available to the participating power utilities after the completion of the initial tests.

3.0   Verification and validation: methods and results

The GIC forecasting system developed in Solar Shield is enabled by integration of a number of NASA science data products and complex state-of-the-art space physics models (see Tables 1 and 2). Obviously, independent V&V of individual components of the system is beyond the limited capabilities of the Solar Shield team. Each instrument and to a large extent each model used in the system have undergone a thorough calibration, V&V etc. carried out by the primary instrument/model teams. These activities are described in the references given above when discussing each instrument/model. The

Solar Shield team will focus on V&V of the end products of the forecasting system, i.e. on V&V of Level 1 and Level 2 forecast outputs. V&V activities associated with both products are described below.

Although Solar Shield team cannot not carry out V&V of the raw data products generated by the scientific instruments used in the forecasting system, a limitation of the products recently recognized by the heliospheric science community is that extreme solar wind conditions push the measurements capabilities of the SWEPAM (*Skoug et al.*, 2004) used in Level 2 forecasts of the system. More specifically, intense penetrating charged particle radiation background can prevent the optimal operation of the instrument. Non-optimal instrumental operating conditions in turn can cause problems in the accurate detection and characterization of high-speed solar wind streams. Consequently, real-time information about extreme solar wind conditions may be inaccurate or missing altogether. This significant deficiency, unfortunately, cannot be addressed until the replacement of the ACE spacecraft. It is noted that Level 1 GIC forecasts are not impacted by this problem.

Methods

One of the major goals of Solar Shield is to utilize the extensive space physics model pool hosted at CCMC (see http://ccmc.gsfc.nasa.gov/) in finding the optimal combination and setup of the models for GIC forecasting purposes. The optimization is important especially for Level 2 forecasts where several global magnetospheric MHD codes with options for coupling to inner magnetospheric and atmospheric models are available. Further, if the metric used in the optimization is selected appropriately, the analysis also allows for evaluation of the economic value of the forecasting system. This is one of the interesting aspects of the project as the economic impact of space weather and the value of the space weather-related products are important and generally poorly understood subjects (*Lanzerotti*, 2008).

The optimization of Level 2 forecasts is accomplished by finding models and the setup of the models that maximize the so-called utility metric of the forecast. Shortly, the utility metric is defined as

$$U_f = BN_H - CN_{\bar{H}} \qquad (1)$$

where N_H is the number of correct forecasts, $N_{\bar{H}}$ is the number of false alarms, C is the cost of taking mitigating action and B is the benefit from having taken mitigating action when an event occurred (see e.g., *Weigel et al.*, 2006). The evaluation is thus based on forecasting GIC *events* that occur within given forecast windows. The parameters N_H and $N_{\bar{H}}$ are obtained by comparing predictions of historical events to observations whereas parameters B and C are obtained by analyzing the economic impact of GIC on power transmission systems. Then, if for a given level of GIC condition

$$\frac{N_H}{N_{\bar{H}}} > \frac{C}{B} \qquad (2)$$

holds, the utility in Eq. (1) is positive and the forecasting system can be used to seek for monetary gain. The ratio $N_H / N_{\bar{H}}$ in Eq. (2) is called the forecast ratio R_f and the ratio C/B will be called below as the cost-benefit ratio.

The optimization of the forecasting system and the analysis of the economic value has been carried out by the Solar Shield team using an extensive set of ground geomagnetic field observations. The geoelectric field and GIC computed by using geomagnetic recordings enable usage of large amount of data from range of different geomagnetic environments in the optimization (for details see, *Pulkkinen et al.*, 2007a).

The Solar Shield team is implementing also an automatic process analyzing both forecasted Level 2 and observed GIC at North American power transmission system nodes in real-time. In the current implementation of this part of the work, the forecasted Level 2 GIC magnitudes are being captured into a SQL database every 10 minutes. Observed GIC from two North American power transmission system nodes are being queried from EPRI's SUNBURST tool and captured into the SQL database every hour. The two datasets are then lined up according to the given timestamps for comparative analysis. The data are currently collected into a development server housed at NASA/GSFC. Further, the Solar Shield team is developing a prototype data analysis tool that automatically calculates N_H and $N_{\bar{H}}$ for real-time Level 2 validation purposes. Due to the recent very low solar activity, the real-time validation system has been collecting so far only negligible amplitudes of GIC and thus these results are not discussed further below. A more comprehensive analysis of the real-time validation system results will be discussed in the final report of the project.

EPRI has carried out an analysis, to be discussed further in the final report, of the economic impact of different levels of GIC on high-voltage power transmission systems. The analysis which studied impacts on a representative model power grid emphasizes the special role of extreme GIC events. More specifically, the study indicated a steep power-law type increase in economic cost of the damages as a function of increasing GIC level; while for low levels of GIC the forecasting system may not be able to provide economic benefit, for extreme events capable of generating losses measured in tens of billions of dollars the forecasting system and the associated mitigation actions may provide a major benefit. From the metrics viewpoint, the economic analysis provided the parameters *B* and *C* in Eqs. (1) and (2) that are used in the evaluation of the system.
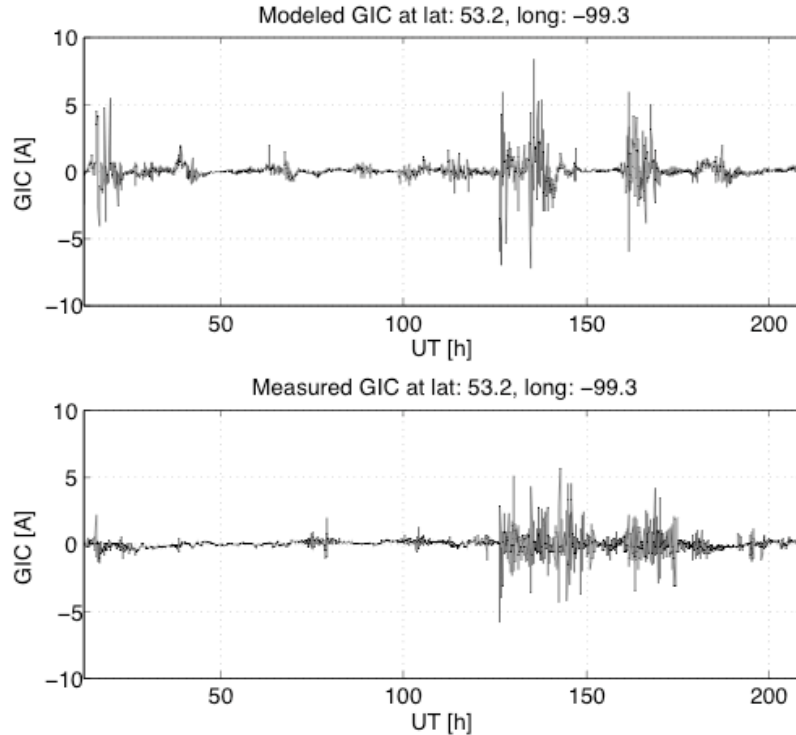
Fig. 4. Predicted Level 2 (top panel) and observed GIC (bottom panel) at one of the North American power transmission system nodes. The time is hours from the beginning of October 24, 2003. It should be noted that the data shown are 4-minute averages. The temporal resolution was set by the frequency at which the magnetospheric MHD model output was saved.

Due to the difference between Level 1 and Level 2 products, the V&V approach described above cannot be applied directly to Level 1 forecasts. Instead, Level 1 GIC forecasts were validated by means of 14 halo CME events (for details of the process, see *Pulkkinen et al.,* 2009). The observed CMEs were used to drive ENLIL and the output were used to determine the start and the end times of the disturbances at the Earth and to compute the probabilities of maximum GIC for two nodes of the North American power transmission system. The two stations are part of the SUNBURST network that provides the observational GIC data used to validate the predictions.

Results

A qualitative view to the capabilities of the Solar Shield Level 2 GIC product is given in Fig. 4 where the predicted and observed GIC at one of the North American power transmission system nodes are given for a sequence of severe space weather storms that occurred during October 2003. It is seen that the predicted GIC amplitudes are comparable with the observed amplitudes and that the timing of the active periods is predicted quite accurately – GIC *events* are reproduced by the forecast. Reproducing the GIC events was an important goal of the activity as was discussed above. Interestingly, also the characteristic complex waveform of GIC is reproduced by the prediction.

A quantitative view to the system's capabilities is shown in Fig. 5 where forecast ratios of 60 minute forecasts for a number of different models and model setups is shown along with the cost-benefit curve provided by the economic analysis carried out by EPRI. The analysis was carried out by using the modeled and observed geomagnetic data (used to compute GIC) for the period of October 24-November, 1, 2003 (for details on the method, see *Pulkkinen et al.,* 2007a), which was one of the stormiest periods on record. Note that only a subset, including the best performing model, of the forecast ratios associated with different model runs carried out at CCMC are shown. The full set of curves will be given in the final report. For a reference, Fig. 5 shows also forecast ratio associated with the persistence model that assumed "always alarm on situation", i.e. in the analysis described above the persistence model always predicts an event for all GIC levels.

From Fig. 5 a number of important observations can be made. First, it is observed that there are significant differences between different models and model setups used to drive the Level 2 GIC forecasts: for example, higher spatial resolution simulations provide larger and more realistic amplitudes of GIC. Further, the global MHD model-based forecasts can perform significantly better in comparison to simple persistence models. The most important observation, however, concerns the relation between the cost-benefit curve *C/B* and the forecast ratios. First, it is seen that there is a significant gap in terms of range of GIC magnitudes between the two. This underscores the difficulty in evaluating the performance of the system for extreme cases: the statistics for rare events is very poor and to evaluate the performance for the most extreme cases, one needs to extrapolate the statistics. However, as can be seen from Fig. 5, a rough exrapolation of the forecast ratios of the best performing models to higher GIC magnitudes indicates that the condition in Eq. (2) holds for extreme GIC events. This in turn indicates that the system can be used to seek for monetary gain. It is emphasized that due to steepness of the cost-benefit curve, even more conservative extrapolations would fullfill the condition (2) for the most extreme cases.
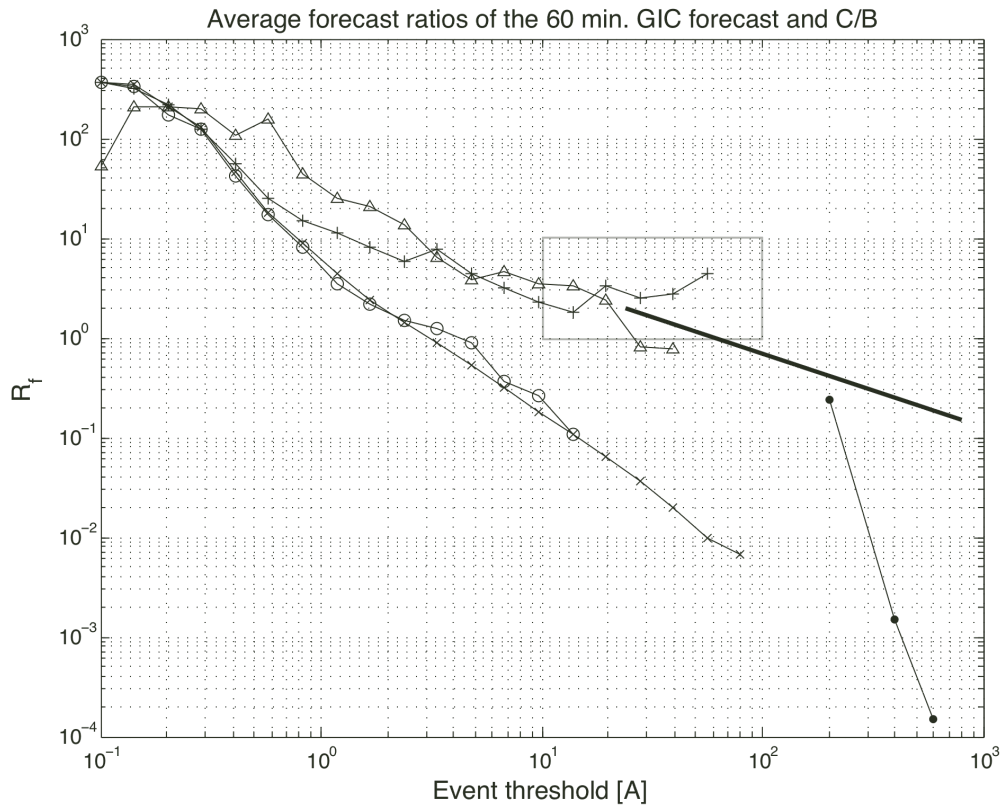
Fig. 5: The forecast ratio R_f obtained by using 60 minute-long forecast windows. Plusses: R_f associated with high spatial resolution BATS-R-US, triangles: R_f associated with low spatial resolution BATS-R-US, circles: R_f associated with OpenGGCM, crosses: R_f associated with the persistence model. The box indicates the approximate R_f associated with Level 1 forecasts. The dots indicate the cost-benefit curve obtained from EPRI's economic analysis of large GIC events. The thick line indicates a rough extrapolation of R_f associated with the best performing models to larger GIC event magnitudes. See the text for details.

The results for the analysis of Level 1 forecasts described above are shown in Fig. 6. For detailed discussion of the results of the analysis, see *Pulkkinen et al.* (2009). It is seen that Level 1 forecasts can give reasonably accurate predictions for the start time of the GIC events; for the analyzed storm events the mean error is about 5 hours. However, the approach systematically underestimated the length of the events, the mean error is about 17 hours. It is noted that changing the definition for the end of an event in the heliospheric modeling part of the approach may help to reduce the systematic bias.

If a "hit" is defined as a prediction for which the observed maximum value falls within the predicted 68 % probability GIC range, the forecast ratios for the stations 1 and 2 are 11/3 and 7/7, respectively. As these forecast ratios correspond roughly to a range of GIC magnitudes between 10-100 A, it can be seen from Fig. 5, quite interestingly, that the range of forecast ratios associated with Level 1 forecasts falls into the ranges similar to those associated with Level 2
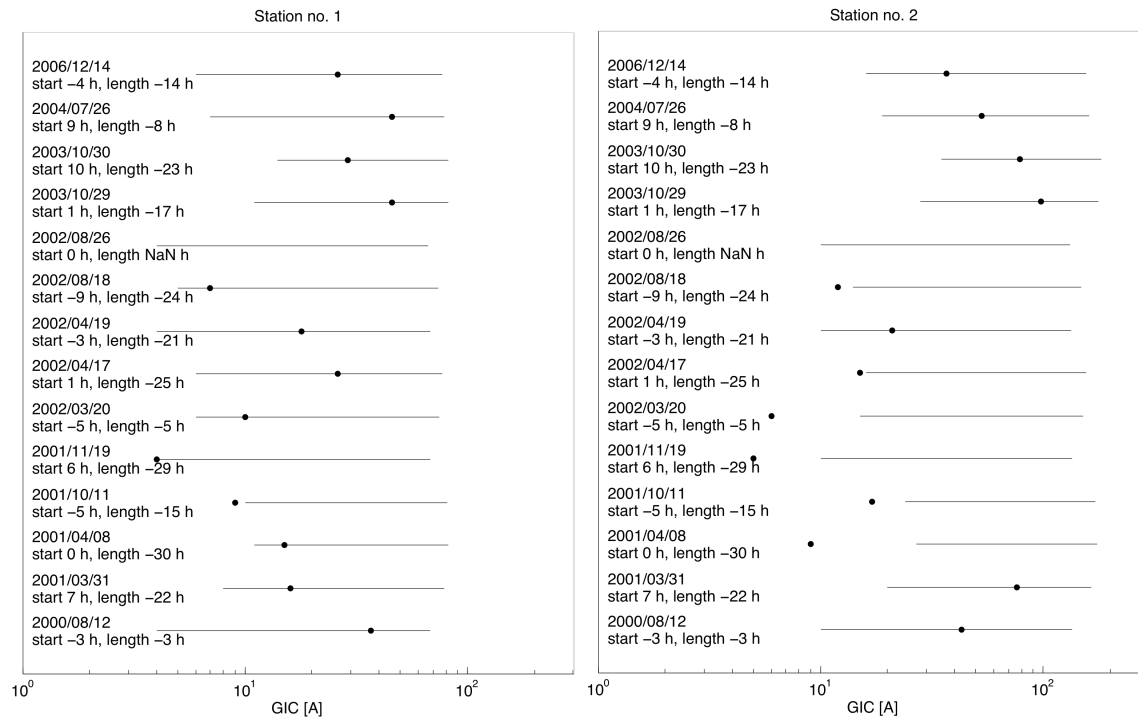
forecasts.

Fig. 6: Results of the Level 1 GIC forecast validation for the two GIC stations (for details of the analysis, see *Pulkkinen et al.*, 2009). Rows give the result for each individual event. Each row shows the date of the event (year/month/day), the error (in hours) in the predicted start time (indicated as "start") and the end time (indicated as "length") of the event. Negative value indicates that the predicted start or end time of the event was earlier than what was observed. The line in each row gives the range of predicted GIC values within which the maximum GIC of the event falls with 68 % probability as given by the lognormal conditional probability distributions. The dot in each row indicates the maximum absolute value of GIC observed during the event. A perfect prediction thus corresponds to start 0 h, length 0 h, and the dot is at the center of the line. There was no GIC event observed on 2002/08/26.

Given the large width of the 68 % probability boundary in lognormal GIC statistics used in the Level 1 forecast approach, forecast ratios of 11/3 and 7/7 for the GIC stations number 1 and 2, respectively, may sound poor. However, it is argued that considering the notable leap taken in the new approach in comparison to earlier efforts, already the fact that the predicted GIC magnitudes are comparable to the observed GIC should be considered as a satisfactory and promising result. Although there clearly is plenty of room for improvement, it is well-justified to state that our capability to model GIC has experienced, along with advances made in general space weather modeling, a significant transition. It is also noted that the Level 1 forecast is not dependent on the accuracy and quality of in situ L1 solar wind observations, which during extreme events

can, as was discussed above, be problematic. Further, the remote solar observations used to drive the cone model and ENLIL do not need to be carried out at L1 and thus the possible disappearance of the current L1-based observational capability does not necessarily cripple Level 1 forecasting approach, unlike Level 2 forecasts.

Finally, it is noted that CCMC is currently leading the Geospace Environment Modeling (GEM) Modeling Challenge in which numerous models are tested by various groups, for example, in terms of the models' capability to generate GIC for large storm events. These analyses will be used to further evaluate Level 2 GIC forecasting capability. The initial results of the Challenge can be found from http://ccmc.gsfc.nasa.gov/support/GEM_metrics_08/reports.php.

4.0   Limitations of the verification and validation process

As was noted above, statistical analysis of rare extreme cases poses a challenge. More specifically, extrapolation was necessary to analyze the data in Fig. 5. Obviously, the extrapolation is subject to uncertainties that are not easy to assess. The only rigorous approach to overcome the shortcoming is to repeat the analysis once more data from extreme storm events has been accumulated.

In the analysis of Level 2 forecasts, the global MHD model output was saved only every four minutes thus dictating the temporal resolution associated with the analysis. As a rule of a thumb, one-minute data should be used in GIC analyses to capture the fluctuations associated with the highest frequencies of the phenomenon. However, saving one-minute output from large number of global MHD runs requires vast amounts of disc space, which was not available for the Solar Shield team. However, it is argued that the central results of V&V are not significantly impacted by this deficiency. Further, in the GEM Modeling Challenge in which the computational and the storage burden is shared among various groups, one-minute global MHD output will be saved and used.

5.0   Conclusions and recommendations

In this activity, an enhancement to the Electrical Power Research Institute's SUNBURST decision support tool used by the U.S. electric power industry is developed by prototyping a Geomagnetically Induced Current (GIC) forecasting system for the effects of solar activity on the North American power grid. The forecasting system consists of a chain of models, which transmit plasma and magnetic fields and their dynamics from the solar surface and heliosphere, to the magnetosphere of the Earth, and then into the Earth's ionosphere. GIC flowing in the power transmission system and the geoelectric field driving GIC is derived from these ionospheric currents. By using real-time space-based observations of near-space conditions and the developed model chain, GIC forecasts can be derived for individual sites of the North American power transmission system. These forecasts, together with other real-time information available via SUNBURST network, can then be used by operators of the transmission system to mitigate the potentially harmful effects of solar activity on the North American grid.

In this document a) the design and the real-time implementation of the forecasting system was described and b) verification and validation activities associated with Solar Shield were described. The established GIC forecasting system is composed of two

partially separate components providing long lead-time Level 1 (1-2 days) and short lead-time Level 2 (30-60 minutes) estimates. Two different approaches for verifying and validating the two levels of the system were devised and executed. The analyses, to be updated periodically as the system is run, indicated that despite the difficulties associated with analyzing rare extreme events, both Level 1 and Level 2 forecast accuracies are good enough to have potential for generating monetary benefit for the user of the system.

It is noted that while the generated forecasting system meets the basic requirements indentified in *Evaluation Report* (2008), the global MHD-based approach to Level 2 forecasts is applicable only for high-latitude locations (for more detailed discussion on this, see *Pulkkinen et al.*, 2007a). Thus, the Solar Shield team recommends a further study on possible usage of the state-of-the-art kinetic inner magnetospheric models in Level 2 forecasts that would provide information also about lower latitude GIC. This topic will be discussed more in detail in the final report of the project.

The work in the activity will continue as outlined in the Solar Shield proposal. As the central part of the work scheduled for years 1-2 of the activity has been carried out, the team will proceed with work scheduled for the year 3. Important elements of the future work will include finalizing the extended SUNBURST DST and establishment of the real-time Level 2 forecast validation system. The team will also use feedback from electric power companies to further streamline the developed GIC forecasting system. The progress in the activity will continue to be reported in scientific peer-reviewed publications and in presentations given in international scientific conferences. The team will provide the final report of the project to NASA as scheduled by the Applied Sciences Program.

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Appendix: Solar Shield publications, presentations and EPO activities

Publications

Pulkkinen, A., M. Hesse, M. Kuznetsova and Lutz Rastätter, First-principles modeling of geomagnetically induced electromagnetic fields and currents from upstream solar wind to the surface of the Earth, *Annales Geophysicae*, 25, 881-893, 2007.

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Pulkkinen, A., and L. Rastätter, On the minimum variance analysis-based propagation of the solar wind observations, submitted to *Journal of Geophysical Research*, 2008.

Pulkkinen, A., A. Taktakishvili, and W. Jacobs, Novel approach to geomagnetically induced current forecasts based on remote solar observations, submitted to *Space Weather*, 2009.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate, and W. Jacobs, Solar Shield - forecasting and mitigating space weather effects on high-voltage power transmission systems, to appear in *Remote Sensing Applications for Societal Benefits*, Ed. S. Habib, Springer, 2008.

Presentations

Pulkkinen, A., M. Hesse, M. Kuznetsova, and L. Rastaetter, First-principles modeling of geomagnetically induced currents from the upstream solar wind to the surface of the Earth, paper presented at 2006 Fall AGU meeting, San Francisco, CA, December 11-15, 2006.

Policelli, F., and A. Pulkkinen, Space Weather and Applications of NASA Heliospheric Data, paper presented at ISRSE, San Jose, Costa Rica, June 28, 2007

Pulkkinen, A., R. Pirjola, and A. Viljanen, Determination of ground conductivity and system parameters for optimal modeling of geomagnetically induced current flow in technological systems, invited paper presented at IUGG 2007, Perugia, Italy, 2-13 July, 2007.

Pulkkinen, A., R. Pirjola, and A. Viljanen, Statistical coupling between solar wind conditions and extreme geomagnetically induced current events, paper presented at fall AGU 2007, San Francisco, 10–14 December, 2007.

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Pulkkinen, A., Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, invited presentation at NASA Goddard Space Flight Center, UMBC/GEST All Hands Meeting, April 3, 2008.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate and W. Jacobs, Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, invited paper presented at Space Weather Workshop, Boulder, CO, April 29 - May 2, 2008.

Damsky, B., Economic Aspects of Space Weather on the Power Grid, invited paper presented at Space Weather Workshop, Boulder, CO, April 29 - May 2, 2008.

Pulkkinen, A., Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, invited presentation at University of Maryland, Baltimore County, Physics Department, October 1, 2008.

Pulkkinen, A., M. Hesse, S. Habib, L. Van der Zel, B. Damsky, F. Policelli, D. Fugate and W. Jacobs, Solar Shield – Forecasting and Mitigating Solar Effects on Power Transmission Systems, NASA Goddard Space Flight Center, Heliophysics Science Director's Seminar Series, December 5, 2008.

Pulkkinen, A., L. Rastätter, M. Kuznetsova and A. Chulaki, GEM Challenge 2008: ground magnetic field perturbations, invited paper presented at mini GEM, San Francisco, CA, December 14, 2008.

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EPO activities

General public article on Solar Shield at http://www.nasa.gov/topics/solarsystem/features/solar_shield.html.

Solar Shield material was prepared for and used in NASA-sponsored Heliophysics Summer School, Boulder, CO, July 23-30, 2008.

Solar Shield material was prepared for and used in NASA Goddard Space Flight Center Visitor Center's Science on Sphere space weather show. A. Pulkkinen presented the show during NASA Launchfest in Sep 13, 2008.